

Energy dependence of hadron spectra and multiplicities in p+p interactions

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The NA61/SHINE experiment at the CERN SPS aims to discover the critical point of strongly interacting matter and study the properties of the onset of deconfinement. In order to reach these goals measurements of hadron production properties are performed in nucleus-nucleus, proton-proton and proton-nucleus interactions as a function of collision energy and size of the colliding nuclei.

Inclusive spectra of identified hadrons in p+p interactions at the SPS energies are presented as a function of transverse momentum, transverse mass and rapidity. The results are compared with the world data and theoretical models.

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[†]A footnote may follow.

1. Experimental data and analysis methods

This paper presents inclusive spectra of identified hadrons produced in inelastic p+p interactions at 20, 31, 40, 80, 158 GeV/c. Three analysis methods were used:

- For π^- spectra the h^- method [1], which is based on the fact that the majority of negatively charged particles are π^- mesons. The contribution of other particles is subtracted using calculations based on the EPOS model [2],
- for π^+ , π^- , K^+ , K^- and p , \bar{p} the dE/dx method, which uses information on particle energy loss (dE/dx) in the TPC gas to identify particles,
- for π^+ , π^- , K^+ , K^- and p , \bar{p} the $tof - dE/dx$ method, which in addition to the dE/dx information uses time of flight (tof) measurements. Combined $tof - dE/dx$ analysis provides excellent separation of different hadron species close to the mid-rapidity region.

Results were corrected for trigger and event selection biases, contribution of non-target interactions as well as detector inefficiencies and feed-down from weak decays and secondary interactions.

2. Results on single-particle spectra

Spectra of transverse mass m_T of negatively and positively charged pions, kaons, protons and Λ hyperons produced in inelastic p+p interactions at 158 GeV/c at mid-rapidity are presented in Fig. 1 (left). The corresponding data for central Pb+Pb collisions measured by NA49 [3, 4, 6] are shown in the right panel of Fig. 1 (right). These data sets were fitted using the simplified blast wave model parameterization [7]: $\frac{dN_i}{m_T dm_T dy} = A_i m_T K_1(\frac{m_T \cosh \rho}{T}) I_0(\frac{p_T \sinh \rho}{T})$. The transverse flow velocity β_T was calculated from the equation $\rho = \tanh^{-1} \beta_T$.

The value of β_T is much higher in central Pb+Pb than in p+p reactions. Transverse mass spectra are approximately exponential in p+p interactions. The exponential dependence is modified by the transverse flow in central (7%) Pb+Pb collisions. Transverse collective flow in Pb+Pb can explain the significant spectra shape difference between p+p and central Pb+Pb reactions.

Rapidity distributions of π^- produced in inelastic p+p collisions [1] and energy dependence of the width σ of the rapidity distribution divided by beam rapidity (y_{beam}) or by the hydrodynamic model prediction (σ_{LS}) [8, 9] are presented in Fig. 2. The shape of the rapidity distribution is approximately Gaussian, however the best fit was obtained by a sum of two Gauss distributions. The width of the π^- rapidity distribution divided by beam rapidity decreases with the collision energy. σ/σ_{LS} and σ/y_{beam} are smaller in p+p than in Pb+Pb interactions. No significant difference of the energy dependence is observed for the width of the π^- rapidity distribution in p+p and Pb+Pb interactions.

The results presented in this paper are an important step towards the study of the system size dependence of the signals of the onset of deconfinement observed in central Pb+Pb collisions, the "kink", "horn" and "step" [4, 5]. The π multiplicity at SPS energies shown in Fig. 3 increases faster in central Pb+Pb than in inelastic p+p collisions (kink) and the two dependencies cross each other at about 40A GeV/c.

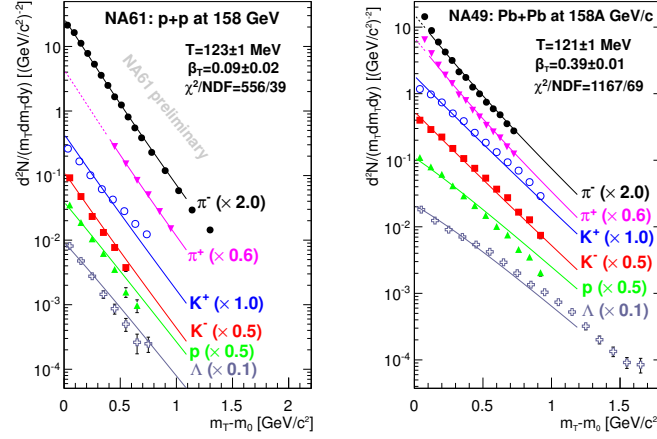


Figure 1: Transverse mass spectra at mid-rapidity measured by the NA61/SHINE experiment in inelastic p+p interactions (left) and corresponding results of NA49 results from central Pb+Pb collisions at 158A GeV (right).

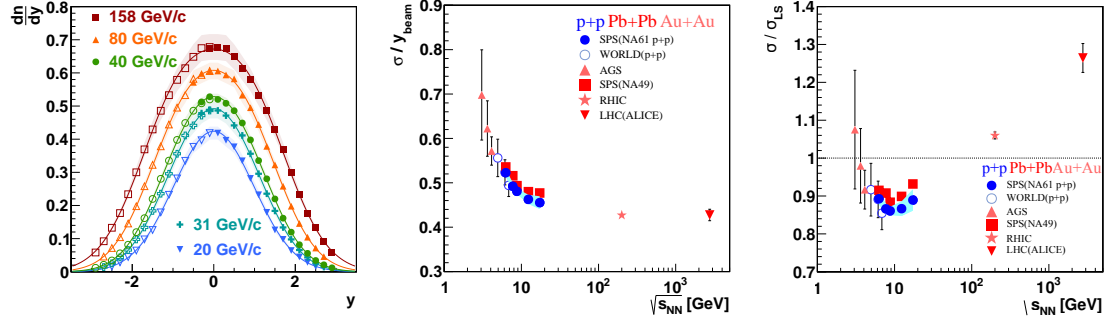


Figure 2: π^- rapidity distributions measured in inelastic p+p collisions at 20, 31, 40, 80 and 158 GeV/c (left). Dependence of the scaled width of the rapidity distribution on collision energy (center and right). World data are taken from Refs. [10, 11, 12]. Results for the width of rapidity distributions are not corrected for isospin effects.

Preliminary NA61/SHINE measurements allow to significantly improve the world data on the inverse slope parameter T of transverse mass spectra of kaons [14] as well as the ratio of K^+ and π^+ yields at mid-rapidity [15, 16].

The m_T spectra were parametrized by the exponential function:

$$\frac{d^2n}{dp_T dy} = \frac{S p_T}{T^2 + m_K T} \exp \left(-\frac{\sqrt{p_T^2 + m_K^2} - m_K}{T} \right), \quad (2.1)$$

where S and T are the yield integral and the inverse slope parameter, respectively. The S and T parameters were fitted to spectra of K^+ and K^- mesons at mid-rapidity as shown in Fig. 4.

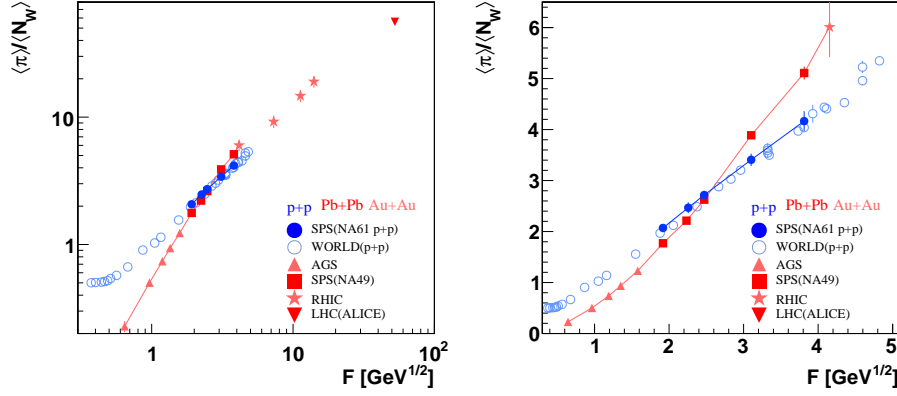


Figure 3: Energy dependence of π multiplicity as a function of collision energy. ALICE points were derived from Refs. [11, 13].

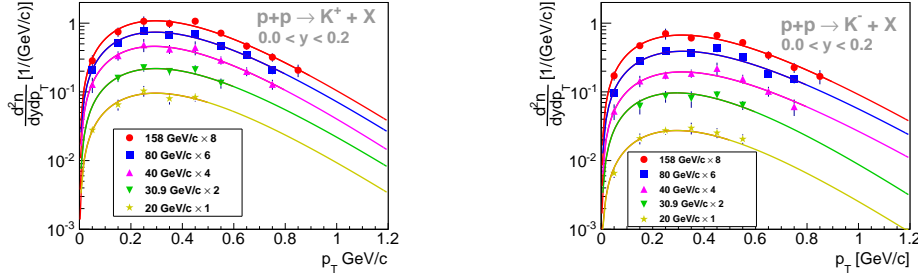


Figure 4: Transverse momentum spectra of K^+ and K^- mesons produced at $y \approx 0$ in inelastic p+p interactions measured by NA61/SHINE.

Figure 5 presents the energy dependence of the inverse slope parameter T of kaons. Surprisingly the NA61/SHINE results from inelastic p+p collisions exhibit rapid changes like observed in central Pb+Pb interactions. World data for p+p and Pb+Pb/Au+Au reactions are plotted for comparison and were taken from Refs. [14, 17, 18, 19].

The acceptance of the identification methods used at the moment by NA61/SHINE does not allow to measure spectra of positive pions close to mid-rapidity. Negatively charged pion spectra were measured by NA61/SHINE [1] using the h^- method. This method cannot be used for positively charged pions due to the large contribution of protons and positive kaons.

Therefore, in order to determine the mid-rapidity yield of positively charged pions the following procedure was used:

- The ratio of measured π^+ and π^- yields was calculated (within the acceptance of the $tof - dE/dx$ and dE/dx methods) and compared with model predictions as a function of collision energy, see Fig. 6. The agreement between the data and the EPOS model [2] predictions is better than 0.1%.

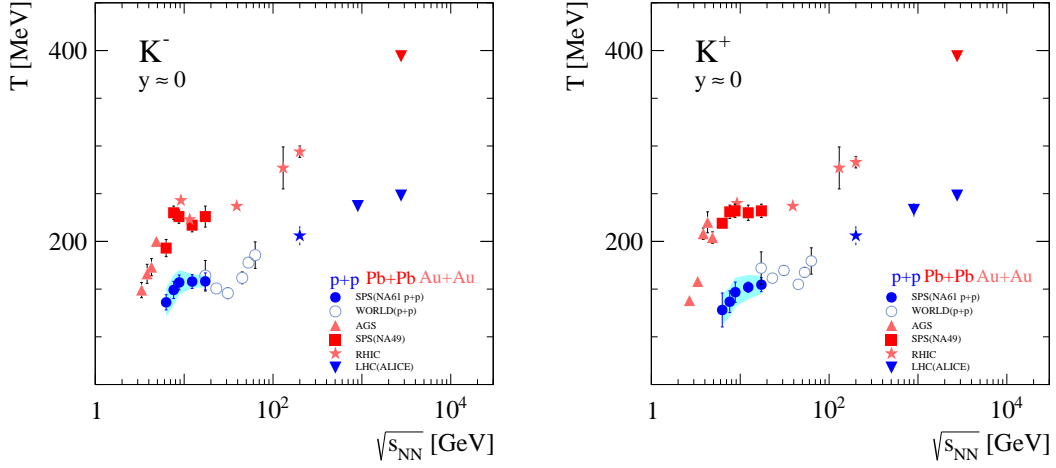


Figure 5: Energy dependence of the inverse slope parameter T of transverse mass spectra of kaons for inelastic p+p interactions and central Pb+Pb/Au+Au collisions.

- The mid-rapidity ratio of the π^+ and π^- yields was calculated from the EPOS model.
- The π^+ mid-rapidity yield was calculated as the product of the measured π^- yield at $y = 0$, the measured $\frac{\pi^+}{\pi^-}$ ratio in the $tof - dE/dx$ acceptance and the EPOS correction factor:

$$\pi^+(y=0) = \pi^-(y=0) \frac{\pi^+}{\pi^-} (tof - dE/dx) C_{MC}, \quad (2.2)$$

where:

$$C_{MC} = \left[\frac{\frac{\pi^+}{\pi^-}(y=0)}{\frac{\pi^+}{\pi^-}(tof)} \right]_{MC} \approx 5\%. \quad (2.3)$$

The final correction factor as a function of energy is shown in Fig. 6.

The energy dependence of the K^+/π^+ and K^-/π^- ratios at mid-rapidity for inelastic p+p interactions and central Pb+Pb/Au+Au collisions is presented in Fig. 7. Surprisingly the NA61/SHINE data suggest that even in inelastic p+p interactions the energy dependence of the K^+/π^+ ratio exhibits rapid changes in the SPS energy range. However, the horn structure is significantly reduced/modified in comparison to that observed in central Pb+Pb collisions. Additionally world data [15, 16, 20, 19, 13] is plotted to establish the trend outside the SPS energy range. The NA61/SHINE results were compared to theoretical models in Ref. [25], namely EPOS [2], UrQMD [22, 21], Pythia 8 [24] and HSD [23]. Figure 8 shows that these models do not describe well the NA61/SHINE results on p+p interactions. The high precision of the measurements should allow for significant improvement of the models.

Proton transverse momentum spectra and mean transverse mass $\langle m_T \rangle$ around mid-rapidity in inelastic p+p interactions at SPS energies are presented and compared with theoretical models in

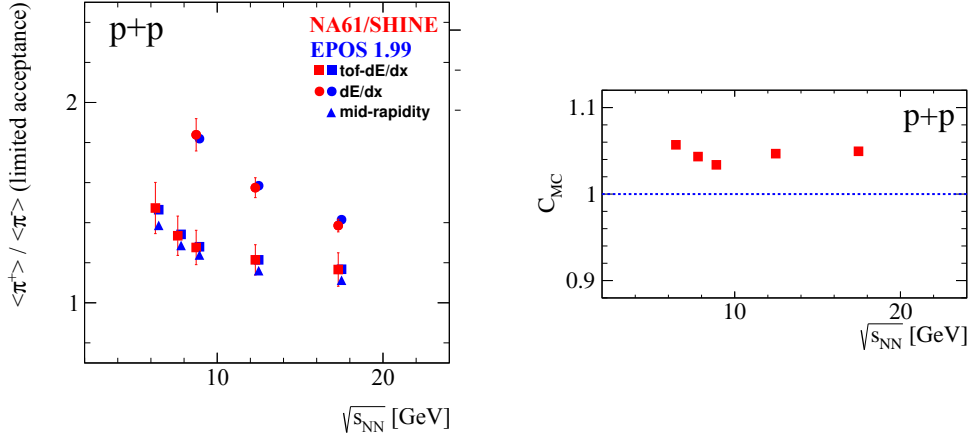


Figure 6: The ratio of π^+ and π^- yields in inelastic p+p interactions as a function of collision energy. The ratio was calculated in the acceptance of the *tof* – dE/dx and dE/dx identification methods. The NA61/SHINE results are compared to predictions of the EPOS model (left). Correction factor used to obtain π^+ yields from the measured π^- yields (right), see Eq. 2.3.

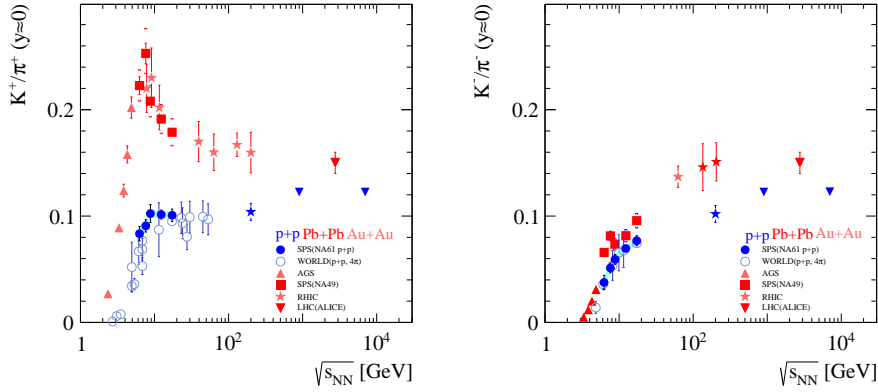


Figure 7: The K^+/π^+ and K^-/π^- ratios in inelastic p+p and central Pb+Pb/Au+Au reactions plotted versus collision energy.

Fig. 9. Mean m_T of protons was calculated from the data parametrization:

$$\frac{d^2n}{dp_T dy} = \frac{S p_T}{T^2 + m_p T} \exp \left(-\frac{\sqrt{p_T^2 + m_p^2} - m_p}{T} \right). \quad (2.4)$$

It increases slowly with collision energy. Neither UrQMD nor HSD describe this behavior [25].

3. Conclusions

The NA61/SHINE measurements show that p+p collisions are unexpectedly interesting. Surprisingly the NA61/SHINE results suggest that even in inelastic p+p interactions the energy depen-

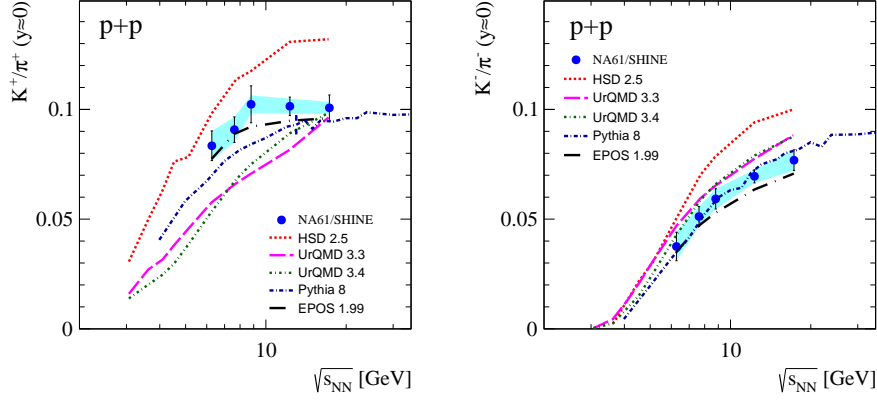


Figure 8: Comparison of K/π ratios in inelastic p+p collisions at SPS energies with theoretical models.

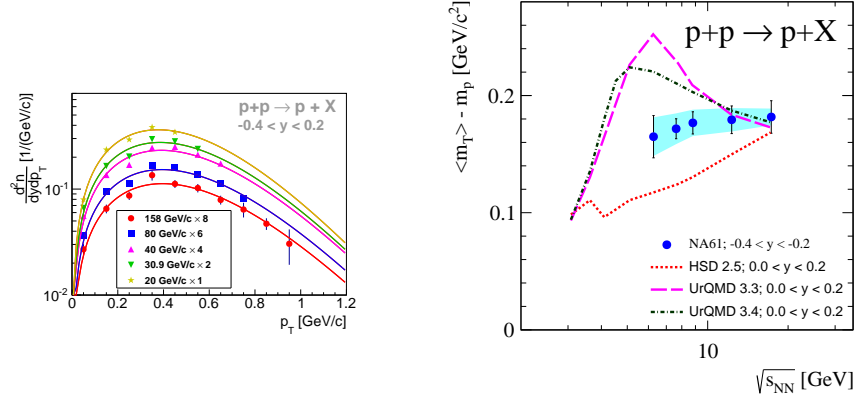


Figure 9: Proton transverse momentum spectra (left) and mean transverse mass m_T (right) around mid-rapidity in inelastic p+p interactions at SPS energies compared with theoretical models.

dence of the K^+/π^+ ratio and the inverse slope parameter of kaon transverse mass spectra exhibits rapid changes in the SPS energy range. However, the structures, e.g. the step and horn, are significantly reduced/modified compared to those observed in central Pb+Pb collisions. High precision NA61/SHINE data present challenges for models and should allow their improvement.

4. Acknowledgments

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